Experimental reflections on water waves

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NPP / NASA GISS

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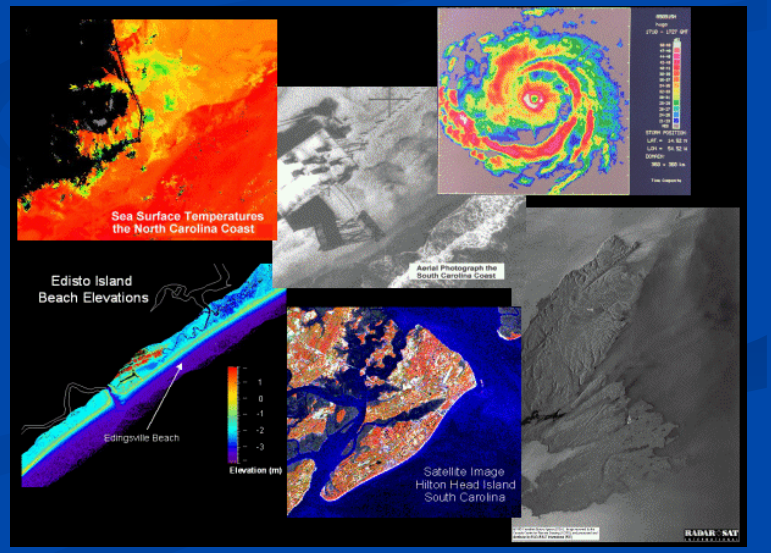
Remote Sensing

is the art of acquiring data
from a distance

Why?

It provides a tool to monitor events on a global scale for:

- Coastal applications
- Oceanic applications
- Hazard assessment
- Natural resource management
- ...



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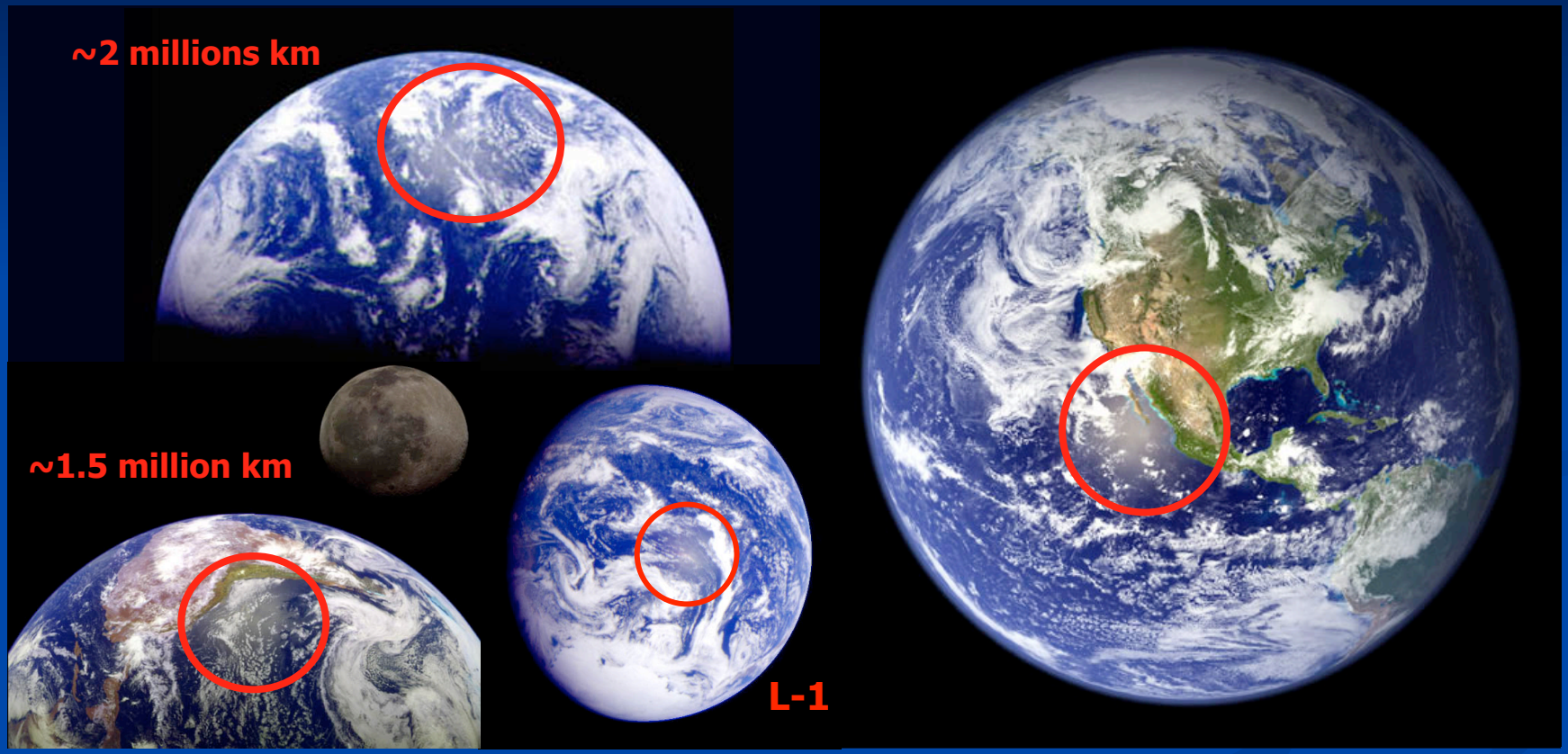
A spacecraft's view

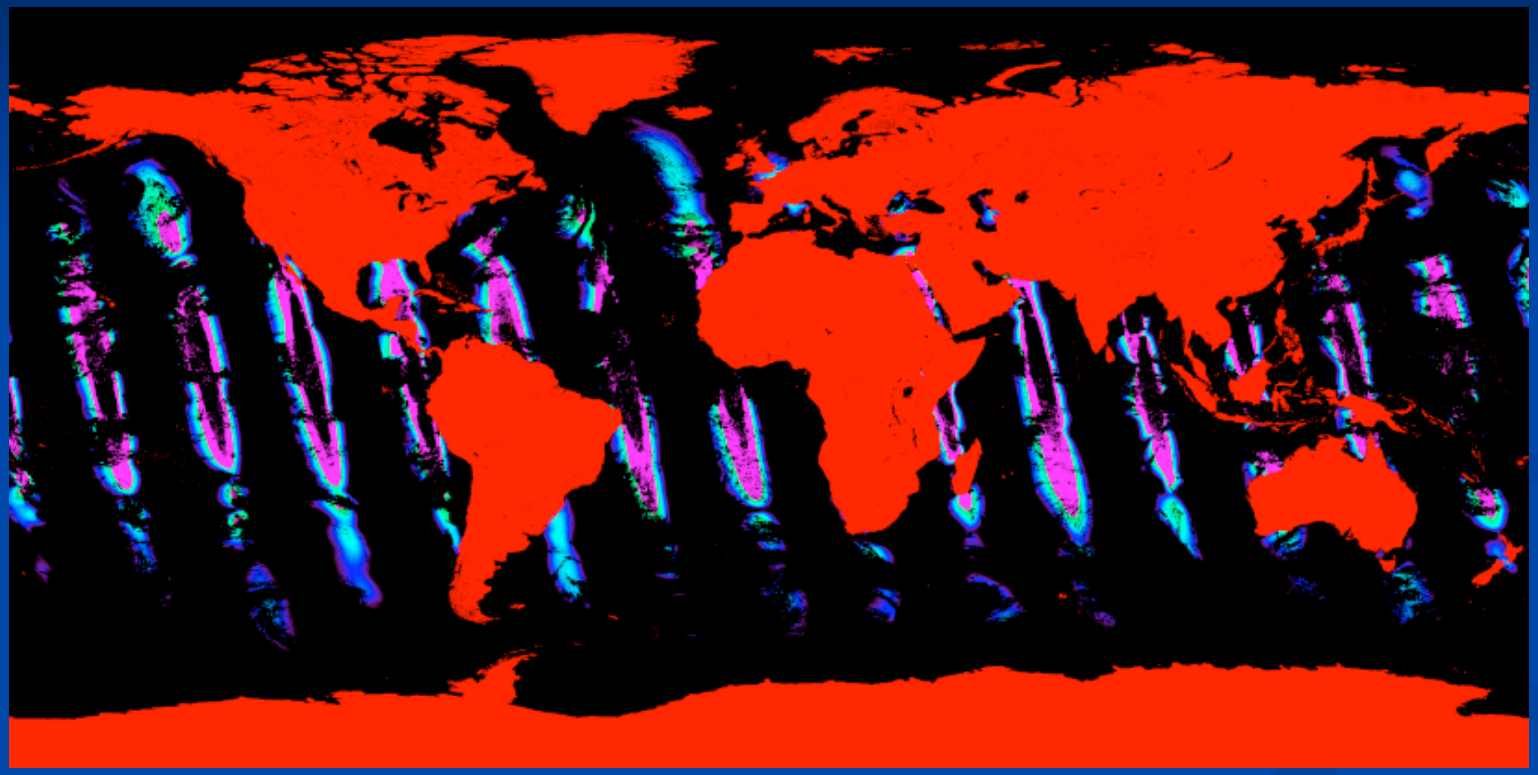


From GALILEO
on its way to Jupiter, 1990

"Blue Marble"
from TERRA (MODIS), 2001

The remote sensor's nemesis

Sunglint is avoided in satellite's imagery due to sensor's saturation



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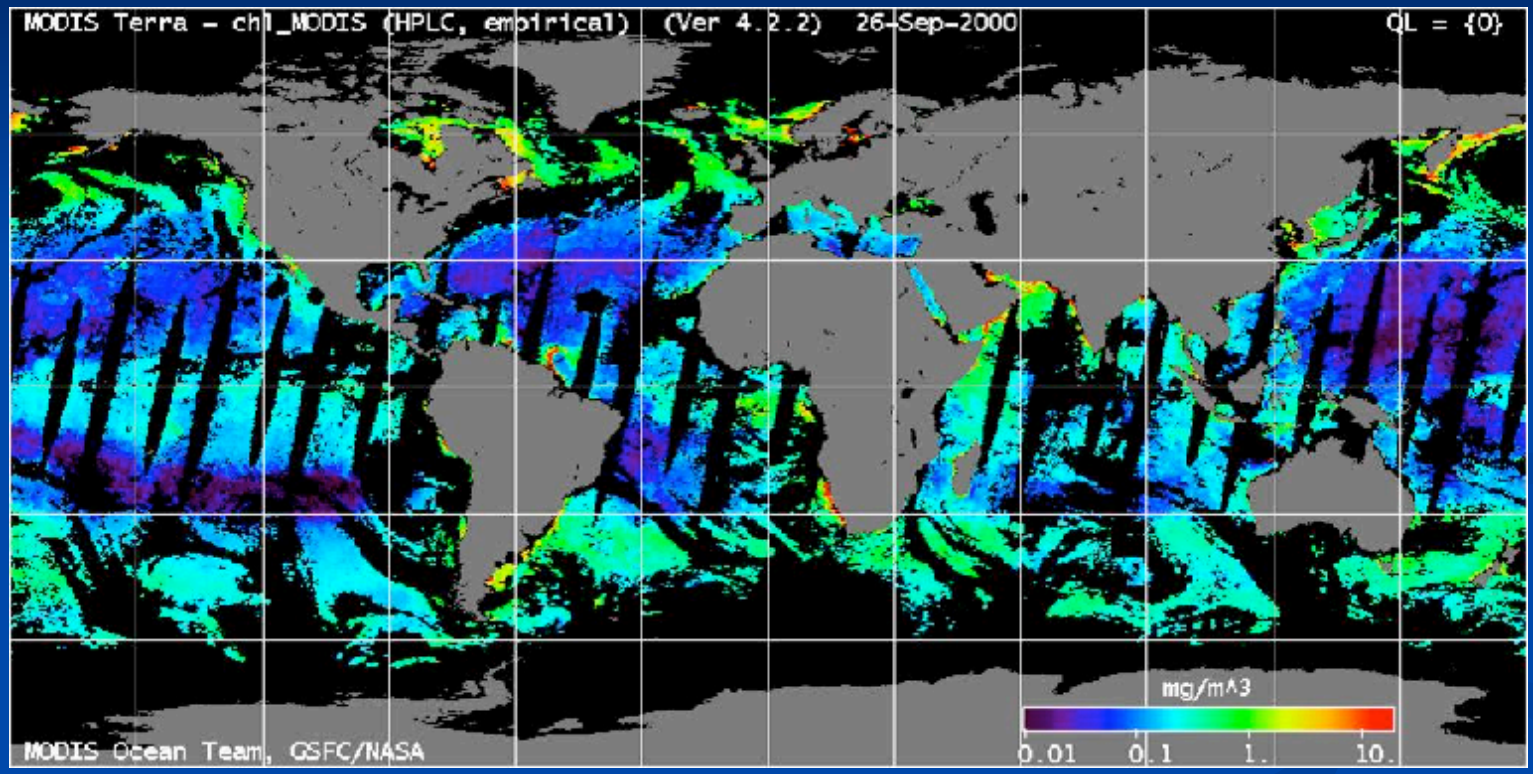

Composite image of the globe by MODIS on-board Terra.

Alternate black swaths are "glint contaminated" data

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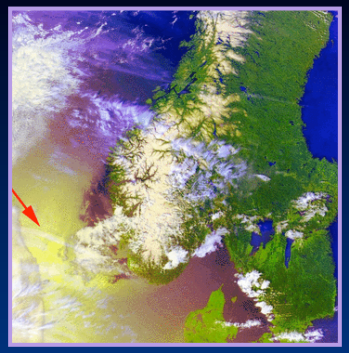
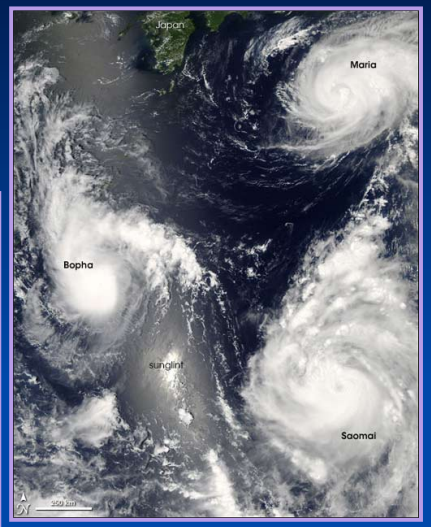
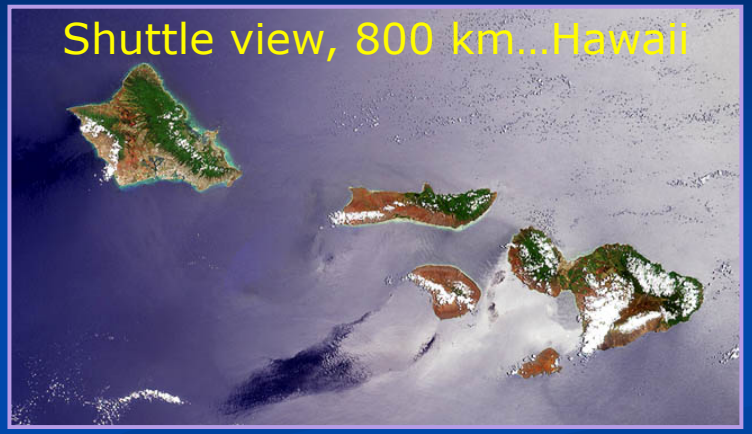
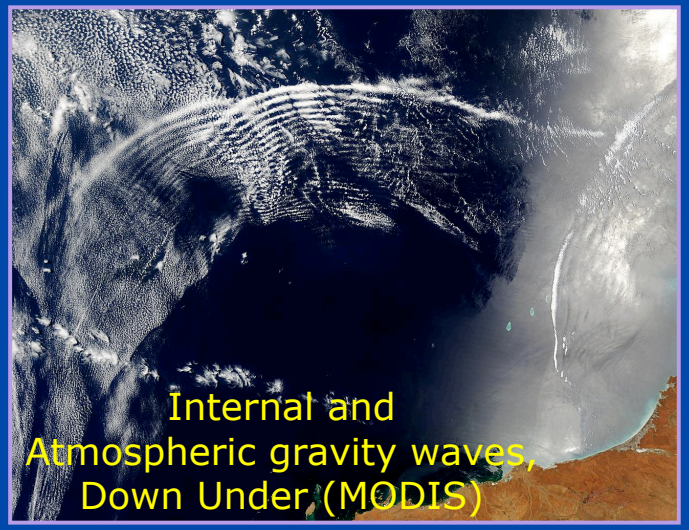
Sunglint from orbit

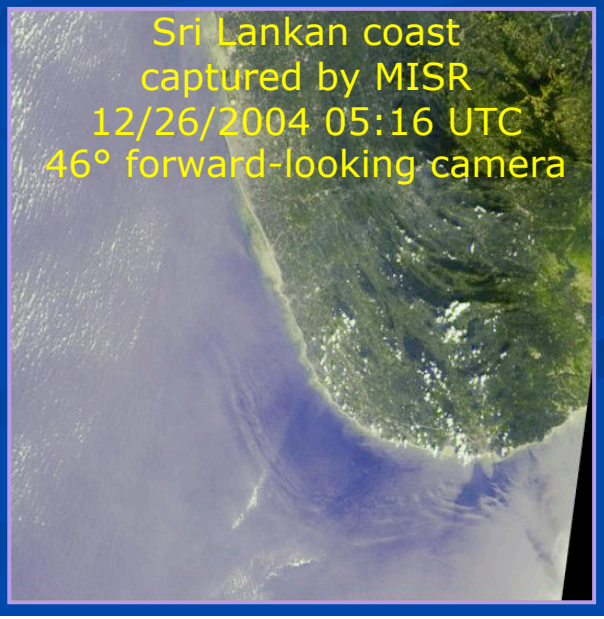
revealing interesting features











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Sunglint down to Earth

…anything from the perfect image of the Sun's disk to a broken pattern

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The “glintometer” apparatus

Ottaviani at el., Journal of Atmospheric and Oceanic Technology (2008)

The idea

Aim a light source at a water surface

to measure the reflected light

under the controlled conditions of a wave tank

Emphasis is on detection of

polarization signatures

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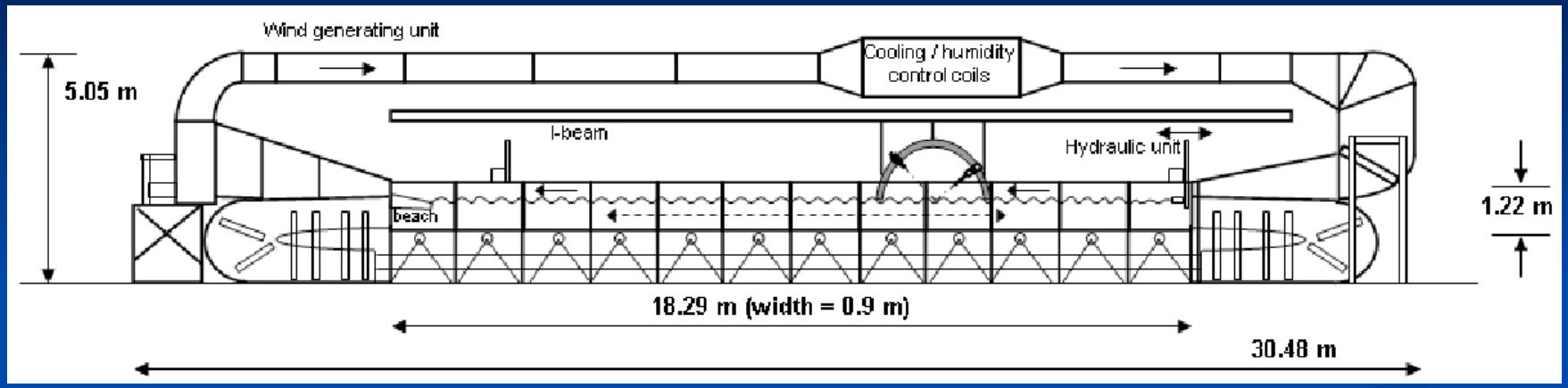
The wave tank at NASA Wallops



Controlled wave states,
ranging from capillary to gravity waves,
are created with:

- a hydraulic unit (frequencies up to 10 Hz)
- a wind flow (up to 18 m/s)
- a subsurface current (up to 0.5 knots)

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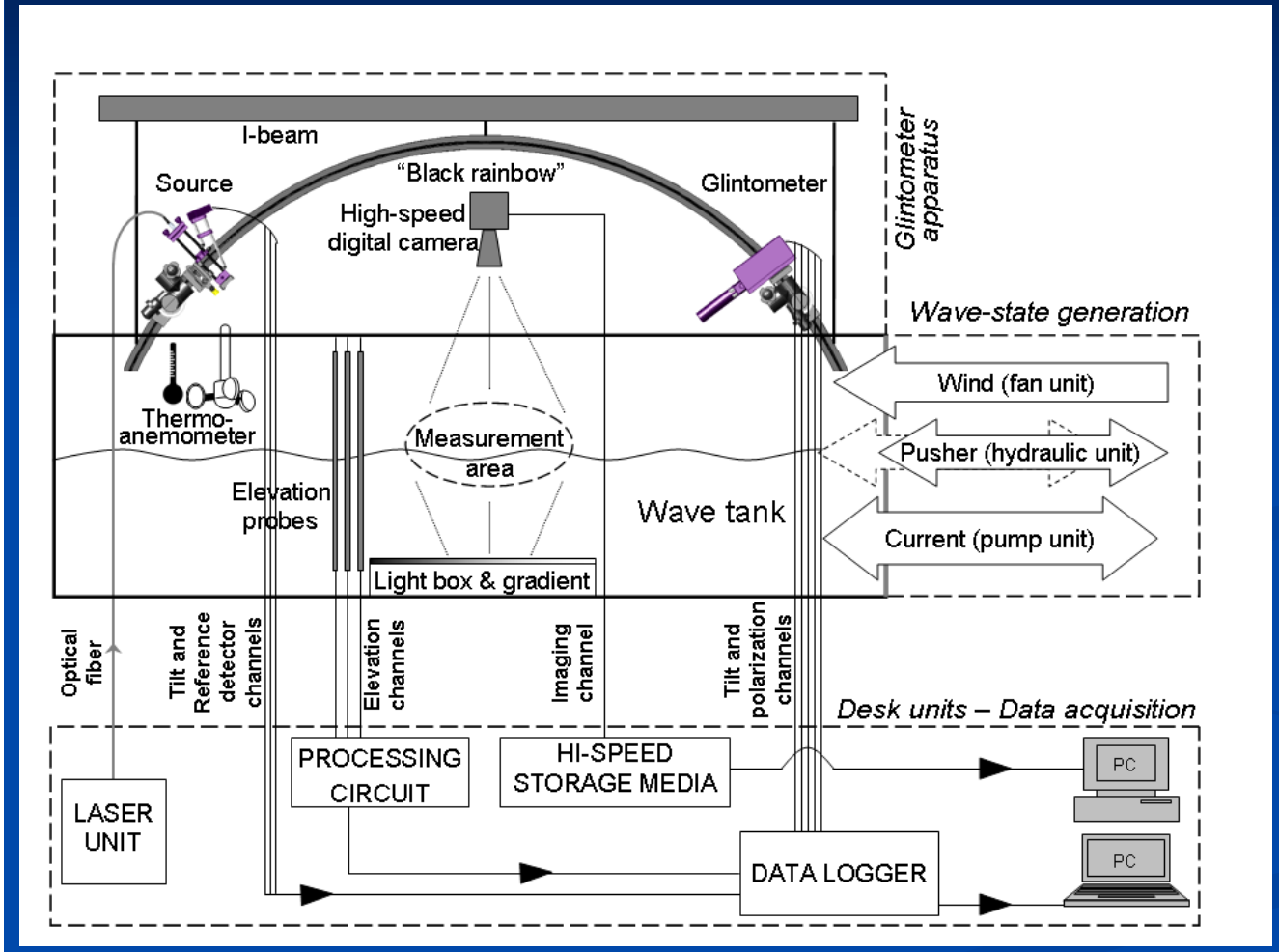
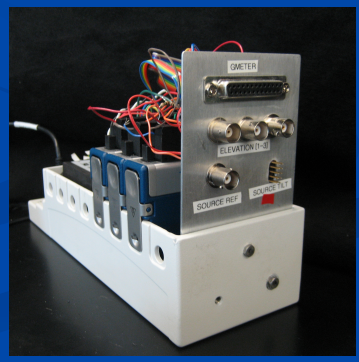
Experimental apparatus - schematics

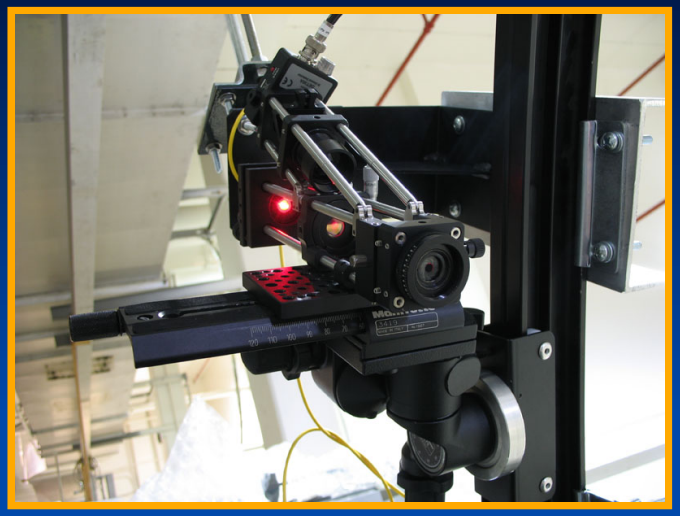


Data logging:

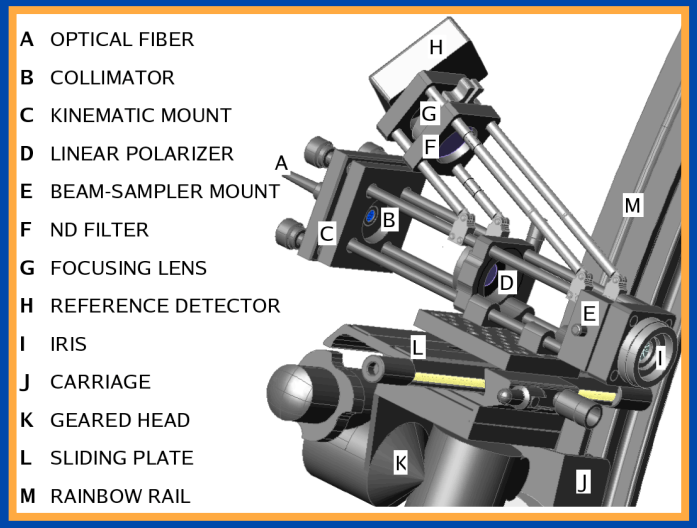
- 3 Intensity channels
- 2 G'meter tilt ch.
- 1 G'meter T.emp. ch.
- 1 Ref. Detector ch.
- 2 Source tilt ch.
- 3 Elevation chs.
- Surface Imaging
- Water, air temperature
- Wind speed

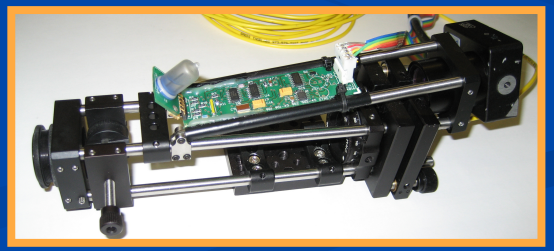


The source



- fiber-coupled laser diode (635 nm)
- polarization state selected by a linear polarizer
- beam diameter controlled by interchangeable collimators
- reference detector sampling the beam for normalization purposes
- Tilt-sensors equipped (pitch & roll)





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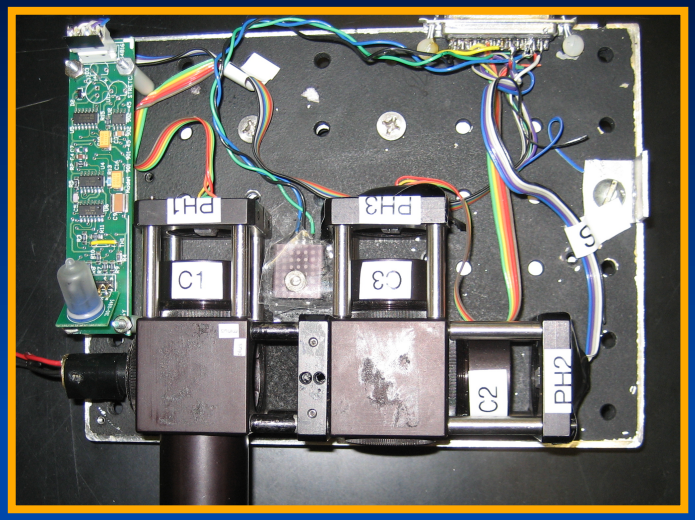
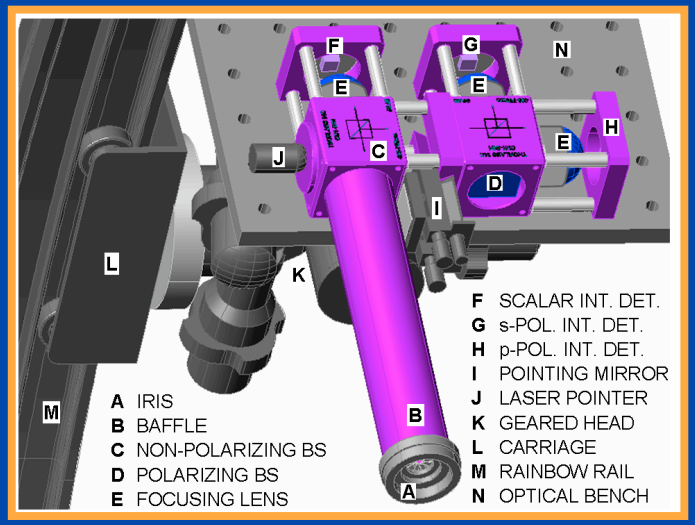
The "glintometer"





- Custom-built photopolarimeter
- A non-polarizing beamsplitter sends 50% of the incoming intensity to a polarizing beamsplitter, to separate s- and p-component
- Simultaneously detects the intensities associated with three of the four elements of the Stokes vector (I, Q, U)
- A fast 16-bit datalogger collects data with suitable sampling frequency.
- Tilt sensor equipped (pitch & roll)

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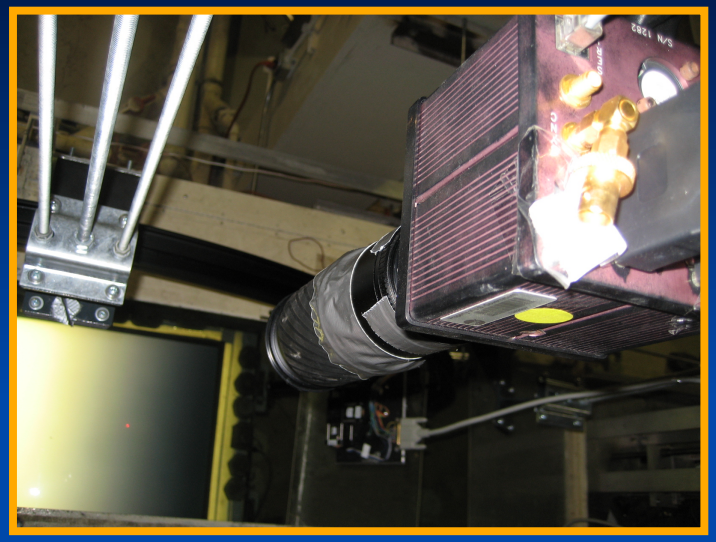
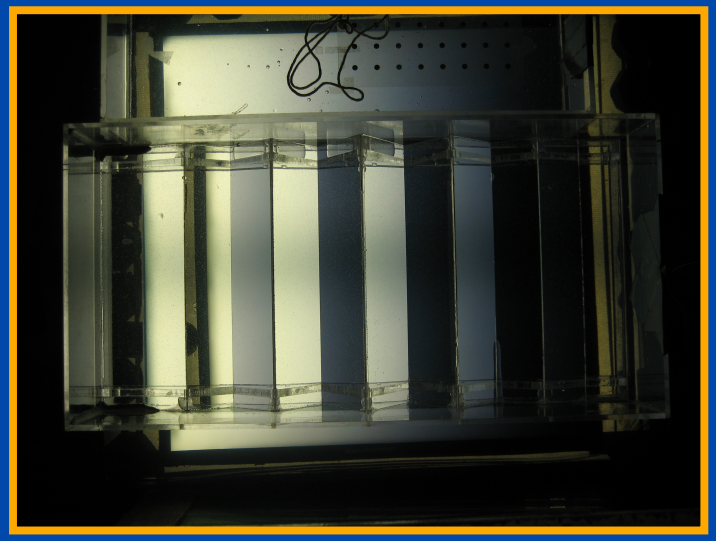
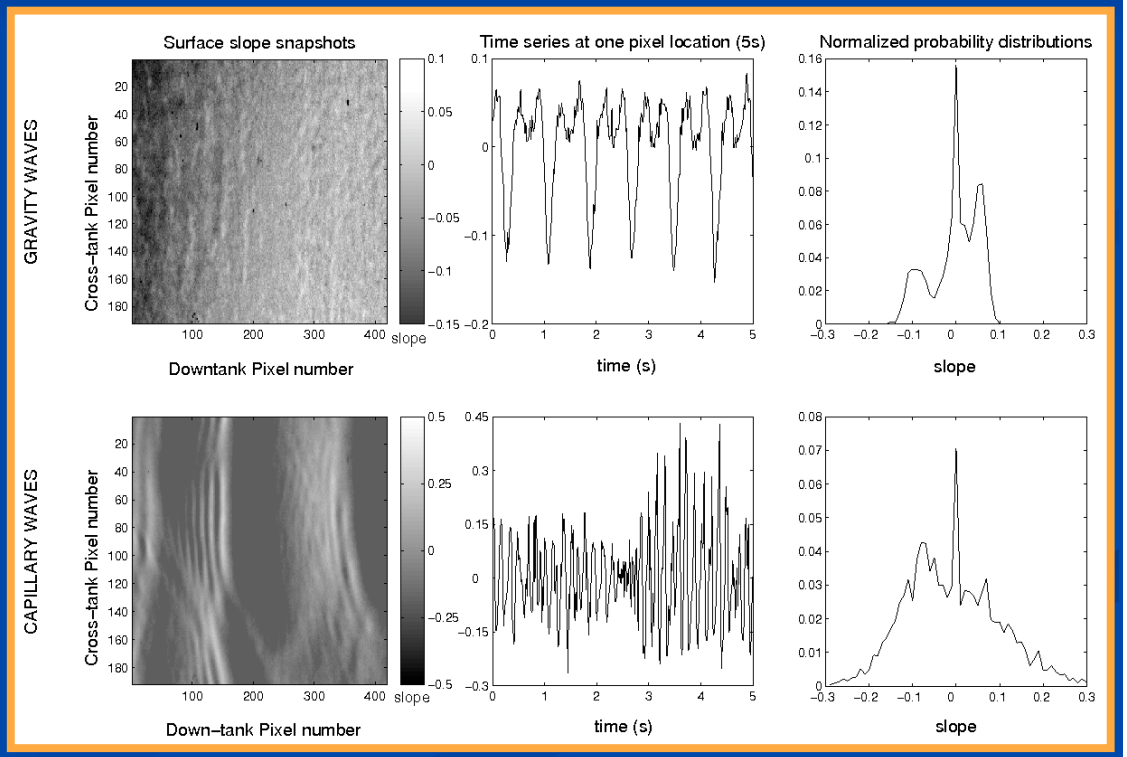
The imaging system





- 12-bit CCD camera, B&W
- 60 fps
- Subsurface, linear-gradient illumination



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Putting it all together

A special mount ("Black Rainbow") has been assembled to move source and detector across polar angles

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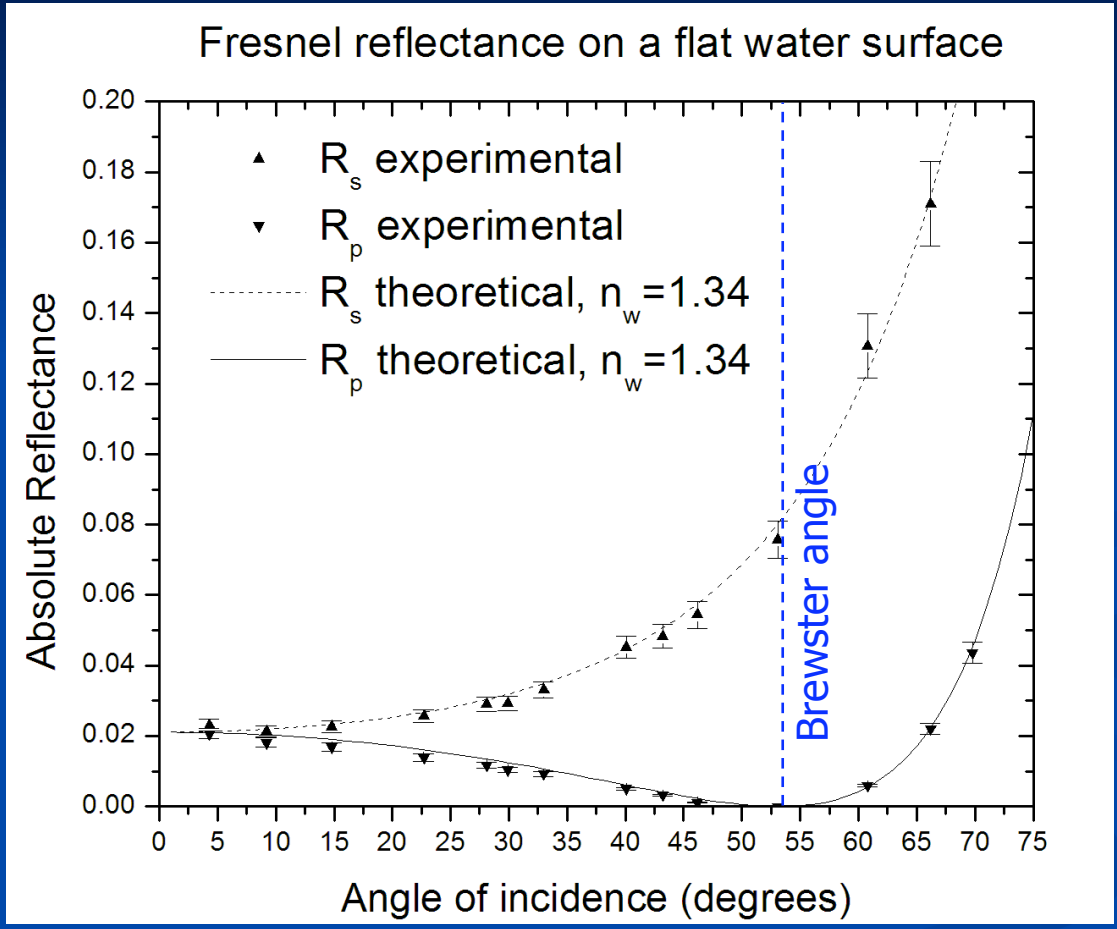
Fresnel reflectance over a flat water surface

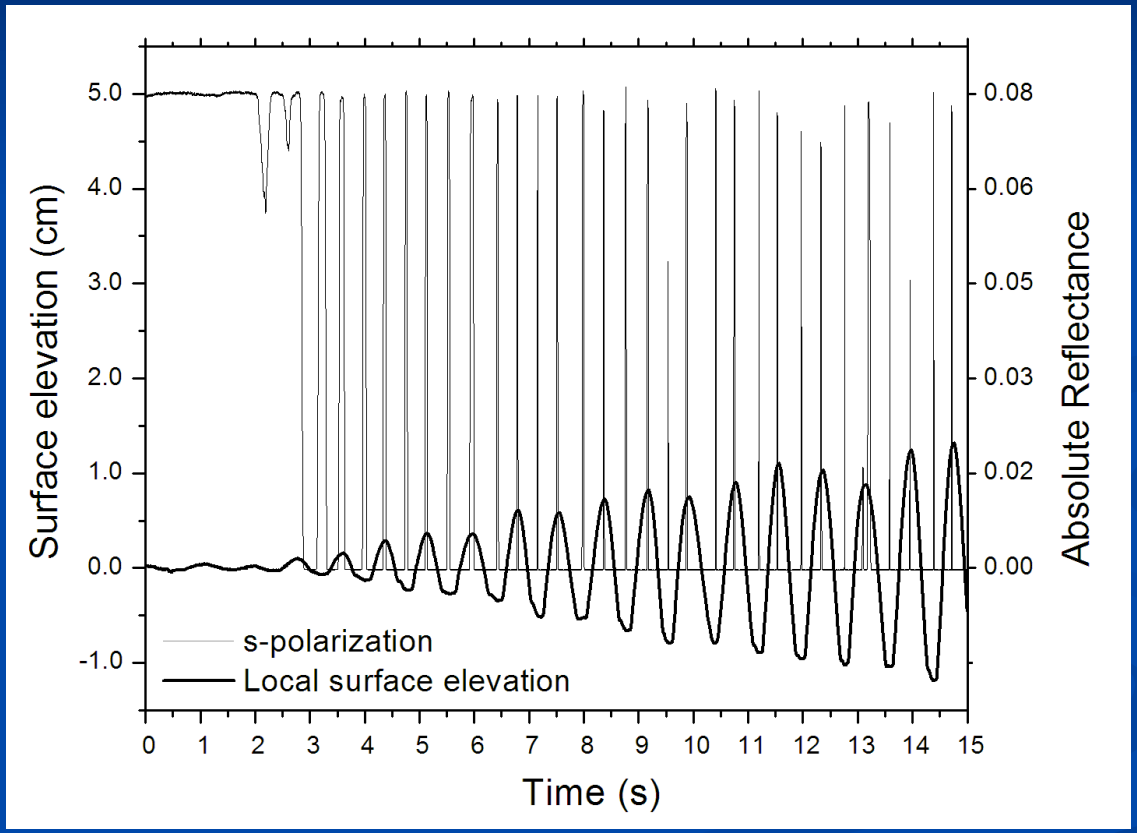


At the Brewster angle, the *p*-component of light is suppressed.

When was such a dataset collected first?

Glints as Fresnel reflectance

Logging the output from the capacitance wires and the photodiodes we obtain an actual representation of the wave profile with glints overlapped with the slopes from which they originate!



Flat surface disturbed as gravity waves start running down the tank

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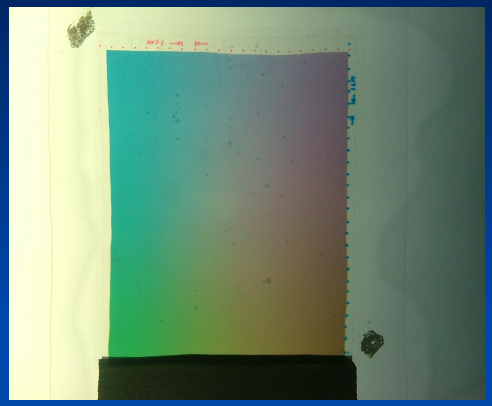
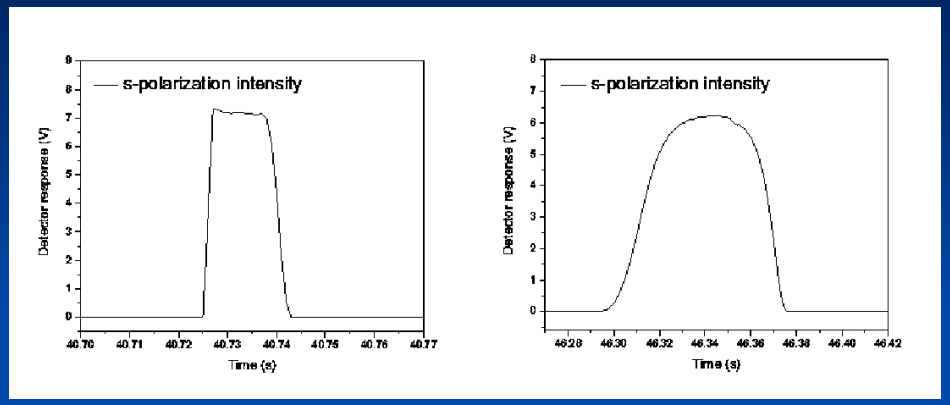
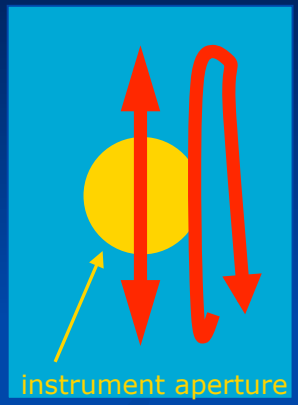
Making waves, the birth of glints

Gravity waves → "Gravity glints"

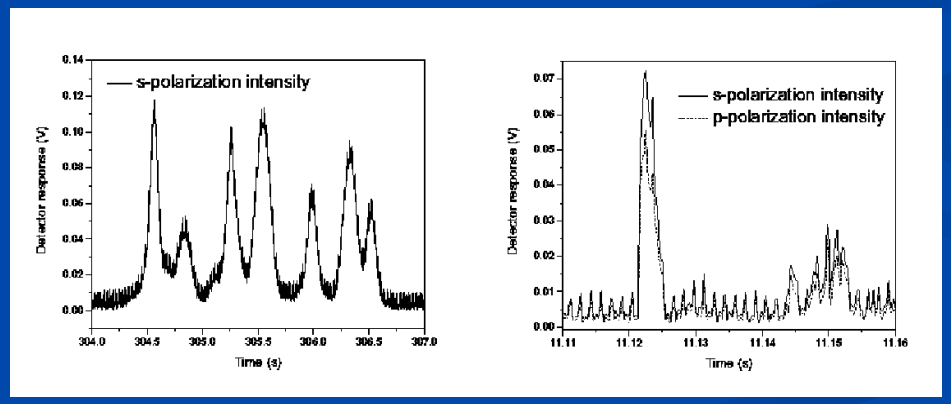




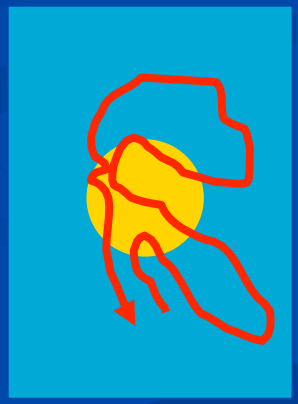
Gravity trajectories



Capillary waves → "Capillary glints"



Capillary trajectories



- Glints exist only when the reflected beam is observed through a limited aperture
- The width (tangential velocity) of glints depends on the observation distance

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Investigation on glint statistics

Ottaviani at el., Applied Optics (submitted, 2008)

Case study

Source and glintometer at 30° from zenith

- Gravity wave state

  1.25 Hz, 1.3 V peak-to-peak signal corresponding to a 2.6 cm piston linear displacement, 1.5 cm total wave height

- Capillary wave state

  Wind speed 3.1 m/s

- Mixed Gravity-Capillary wave state

  Overlap of the states above

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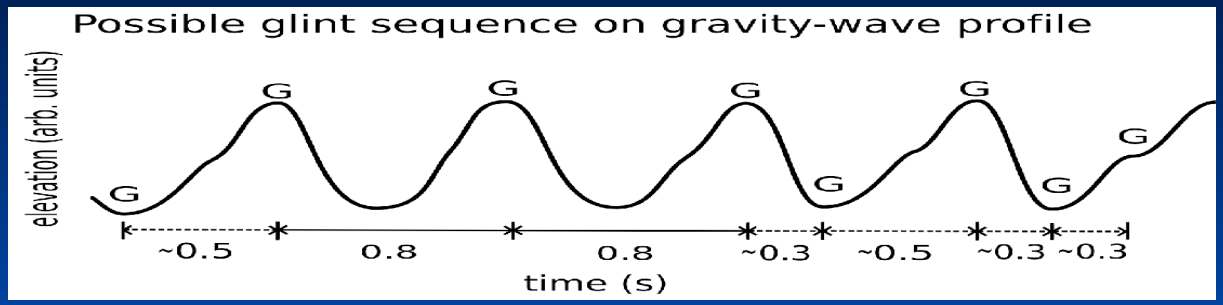
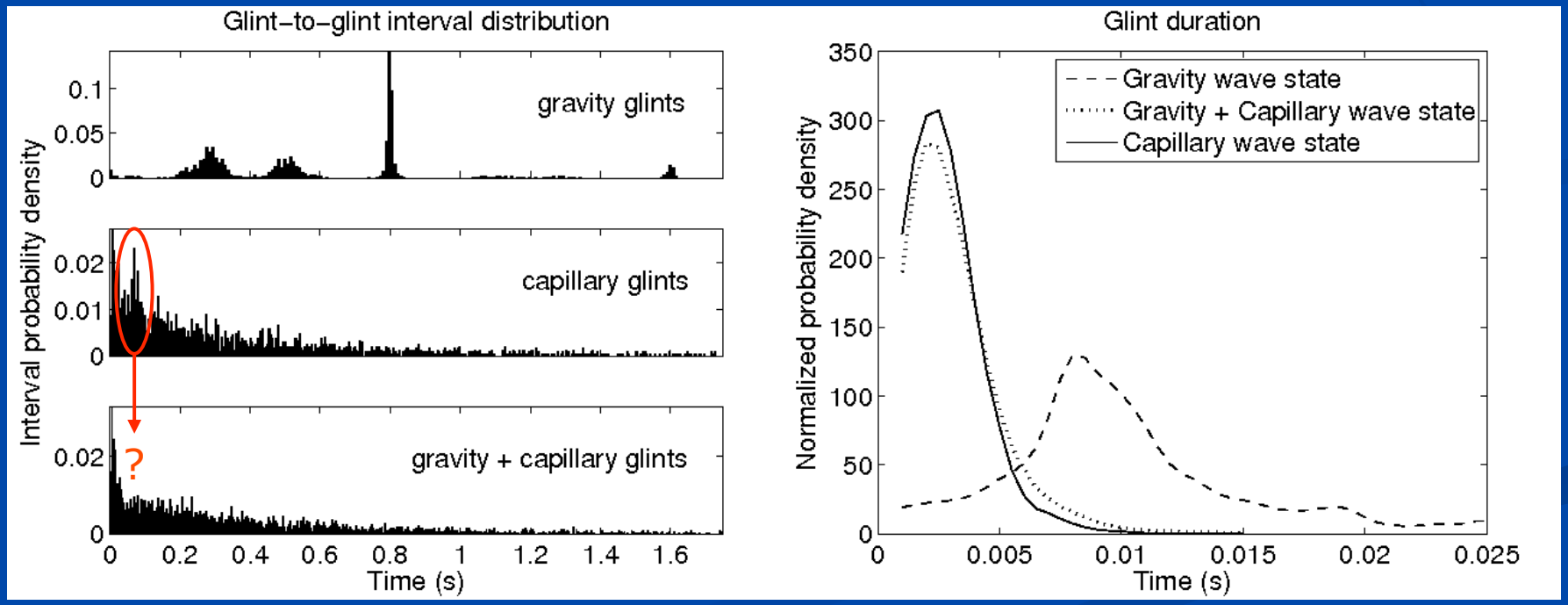
Glint statistics I: glint-to-glint intervals and glint durations



Capillary glints are erratic, and ~10 times more short-lived than gravity glints



Capillary characteristic frequencies spread out in the mixed state

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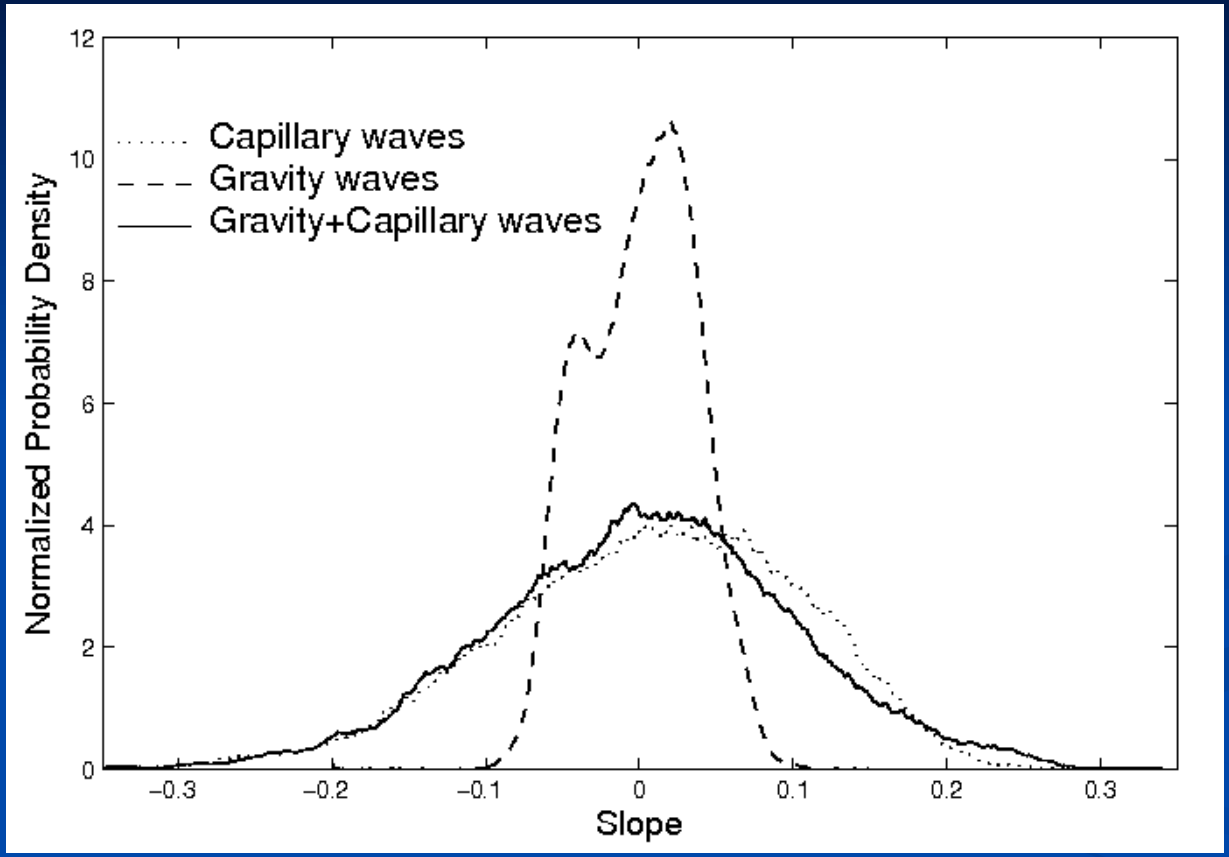
Wave slope distributions



Gravity waves max slope: ±6°

Capillary and gravity-capillary waves max slope: ±17°

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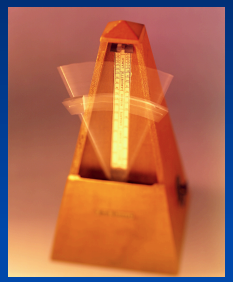
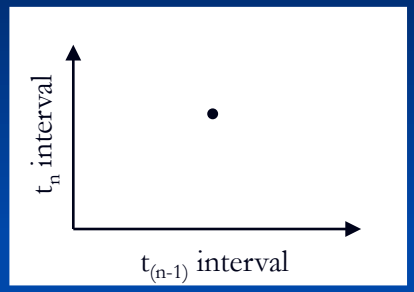
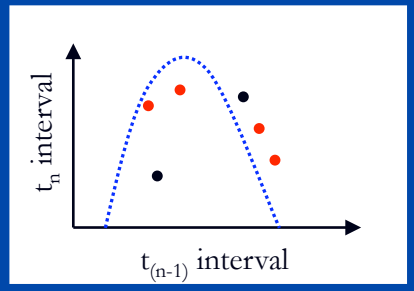
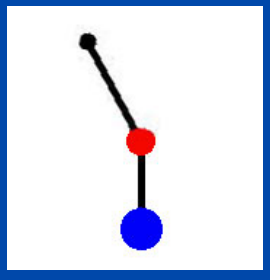
Chaoticity and Attractor plots

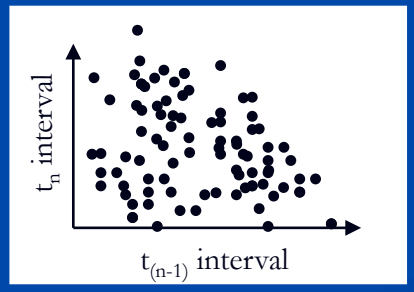
Attractor plots are used to analyze to level of chaoticity of a system, by showing the correlation between intervals

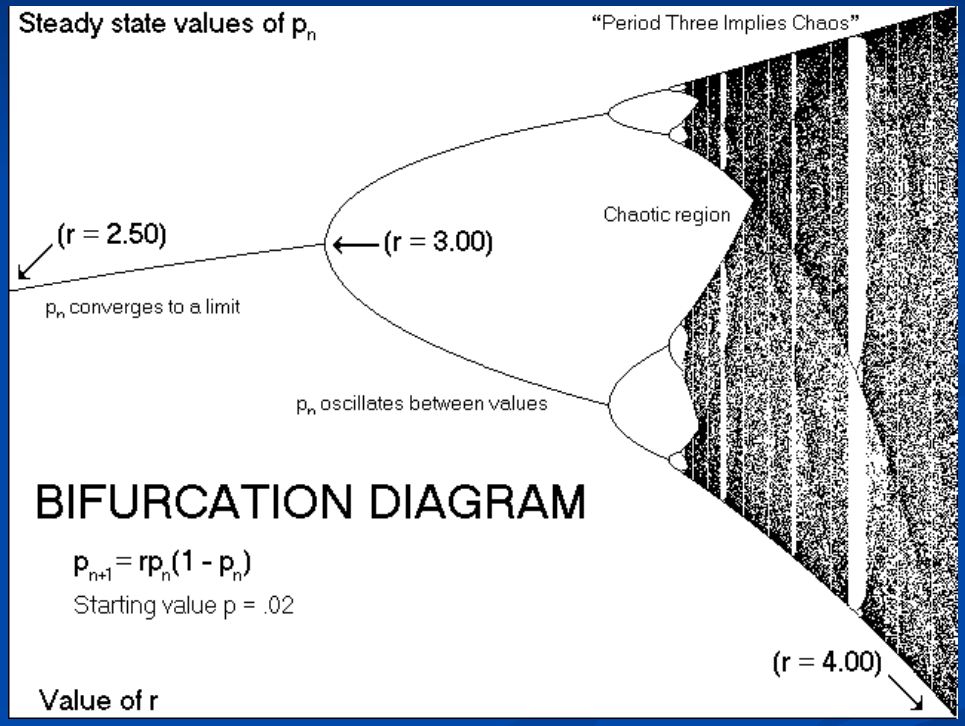












The road to chaos:
bifurcation diagram of the logistic map
(possible long-term population values
of the logistic function)

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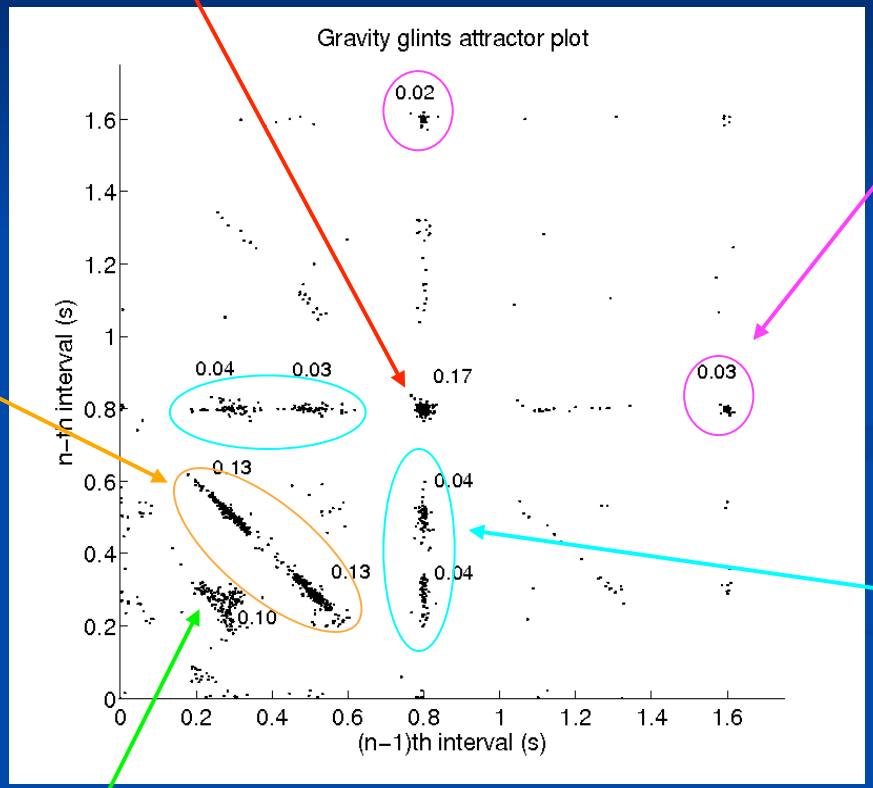
Glint statistics II:
Gravity glints attractor plot

0.8 s interval due to 1.25 Hz paddle frequency (17%)



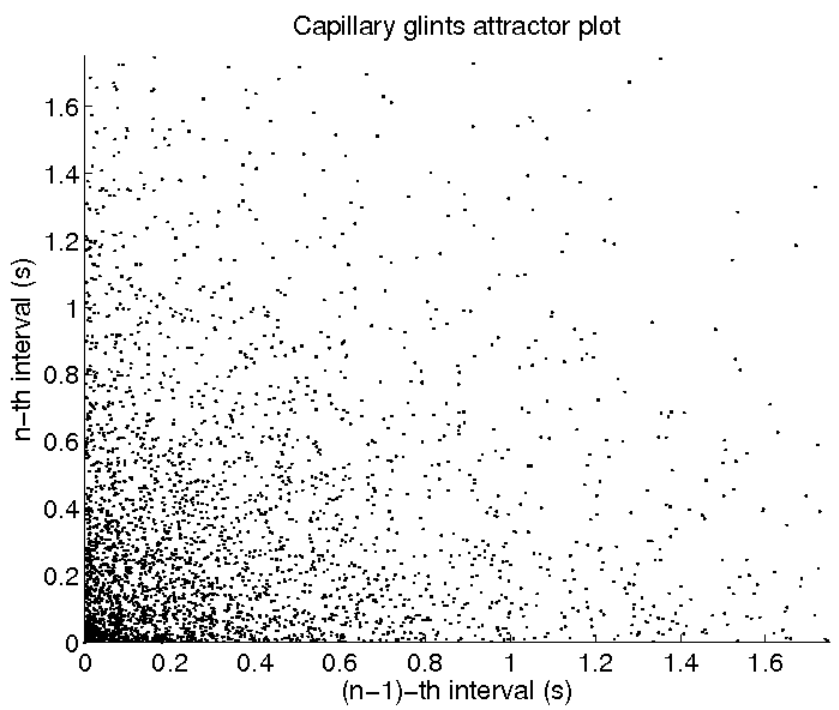
skipping glints for an entire wave period (<1%)

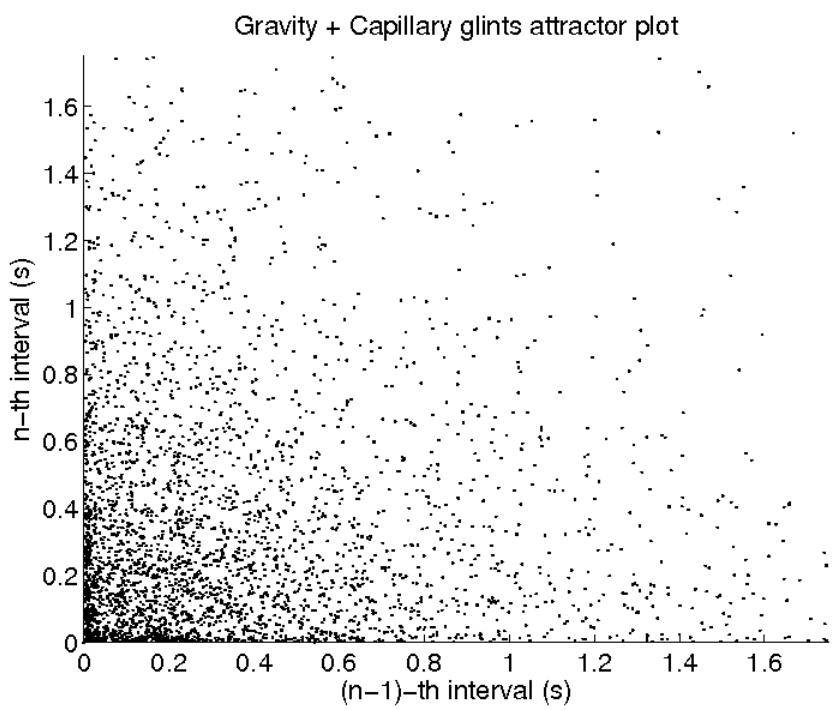
alternating 0.5 and 0.3 s intervals (26%)

skipping glints due to cross-tank components (15%)

overlap of secondary wave component (10%)

Glint statistics II:
Capillary and mixed glints attractor plots





…nearly indistinguishable!

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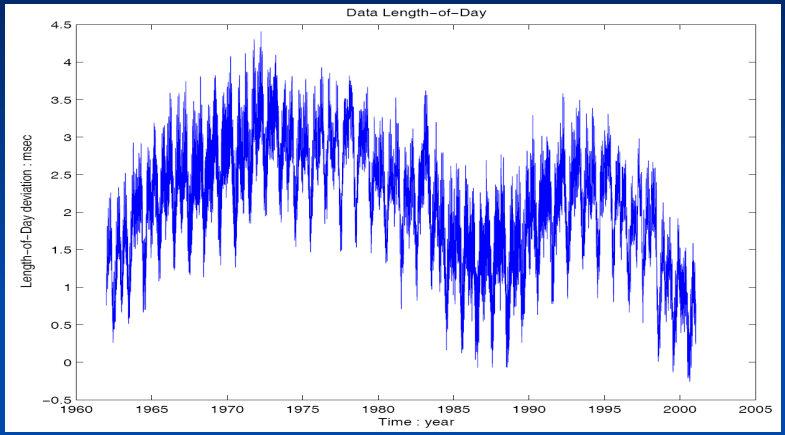
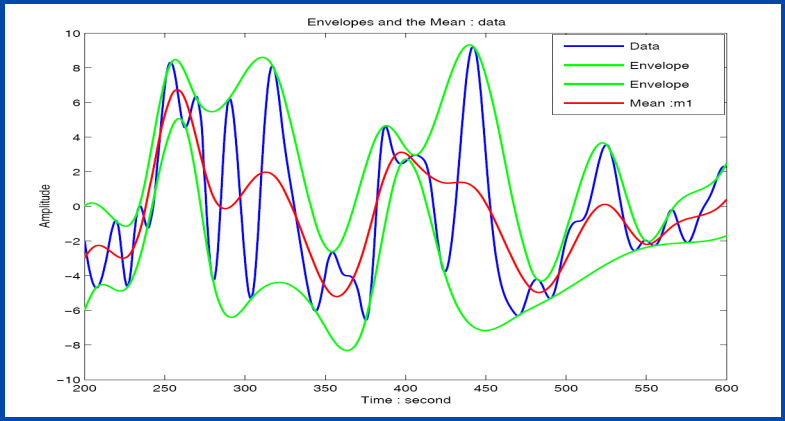
The Hilbert-Huang Transform

Applies to non-linear, non-stationary time series
Gives detailed view of the scales of the phenomenon

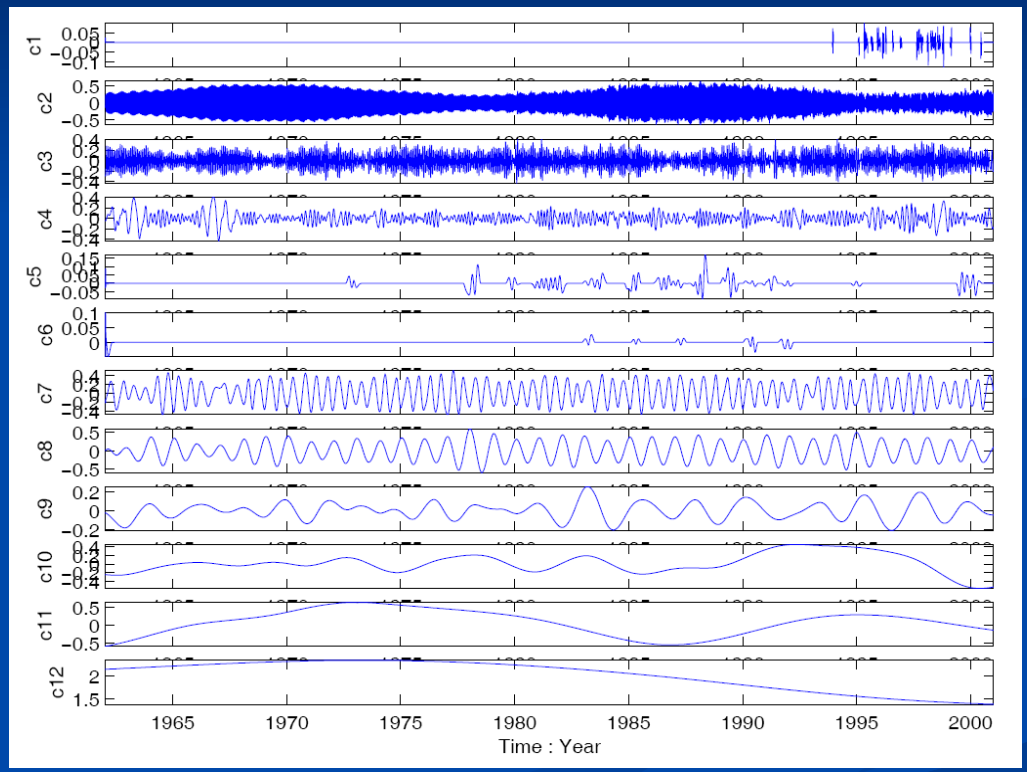


Length Of Day data



Empirical Mode Decomposition

Intrinsic Mode Functions



- c1: Large-scale storms, detectable since '90s
- c2: Half-monthly tides
- c8: Monthly tides (+El Niño events)

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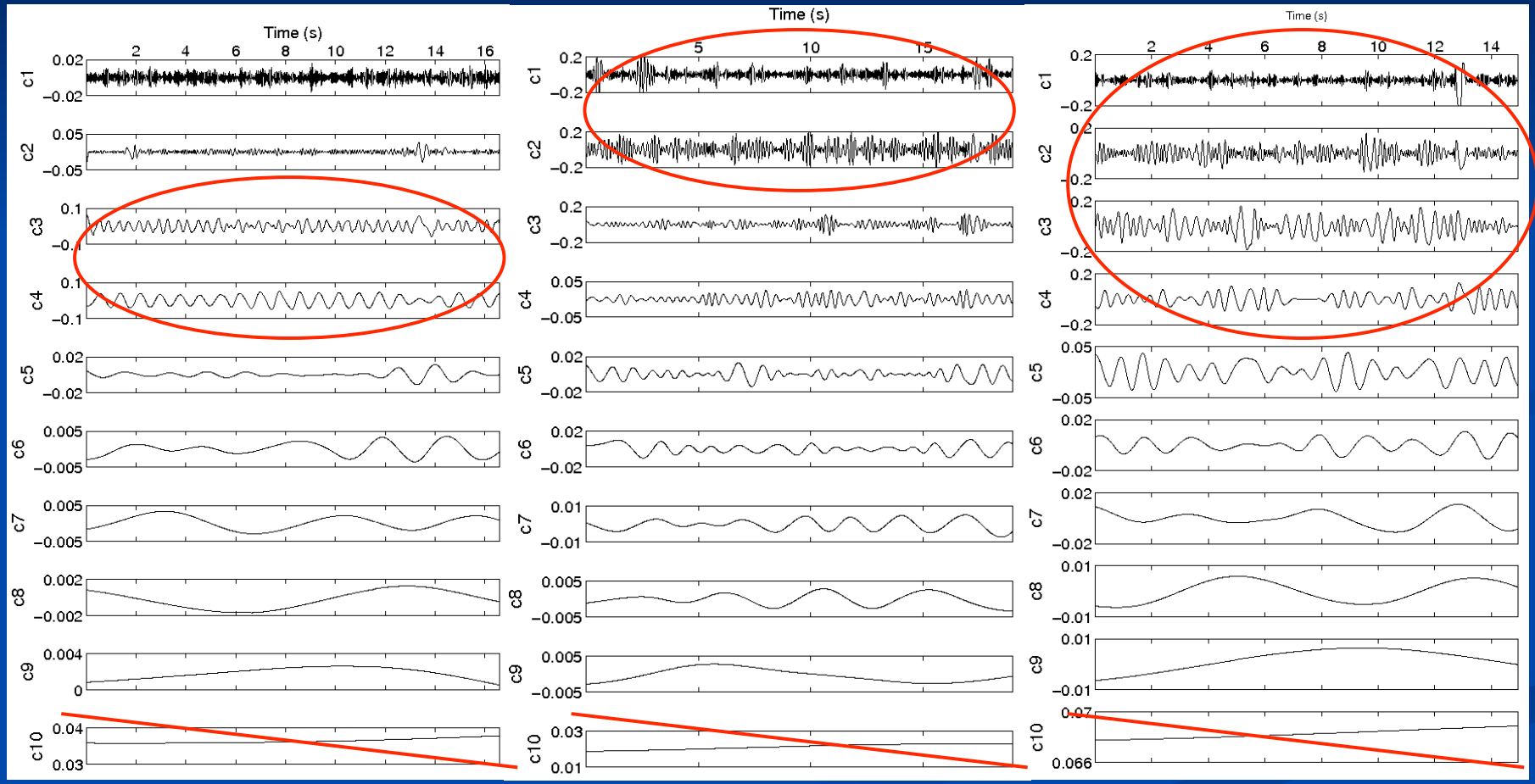
HHT results:

Scale component extracted

Gravity waves | Capillary waves | Gravity-capillary waves



The mixed state exhibits both gravity and capillary scale components

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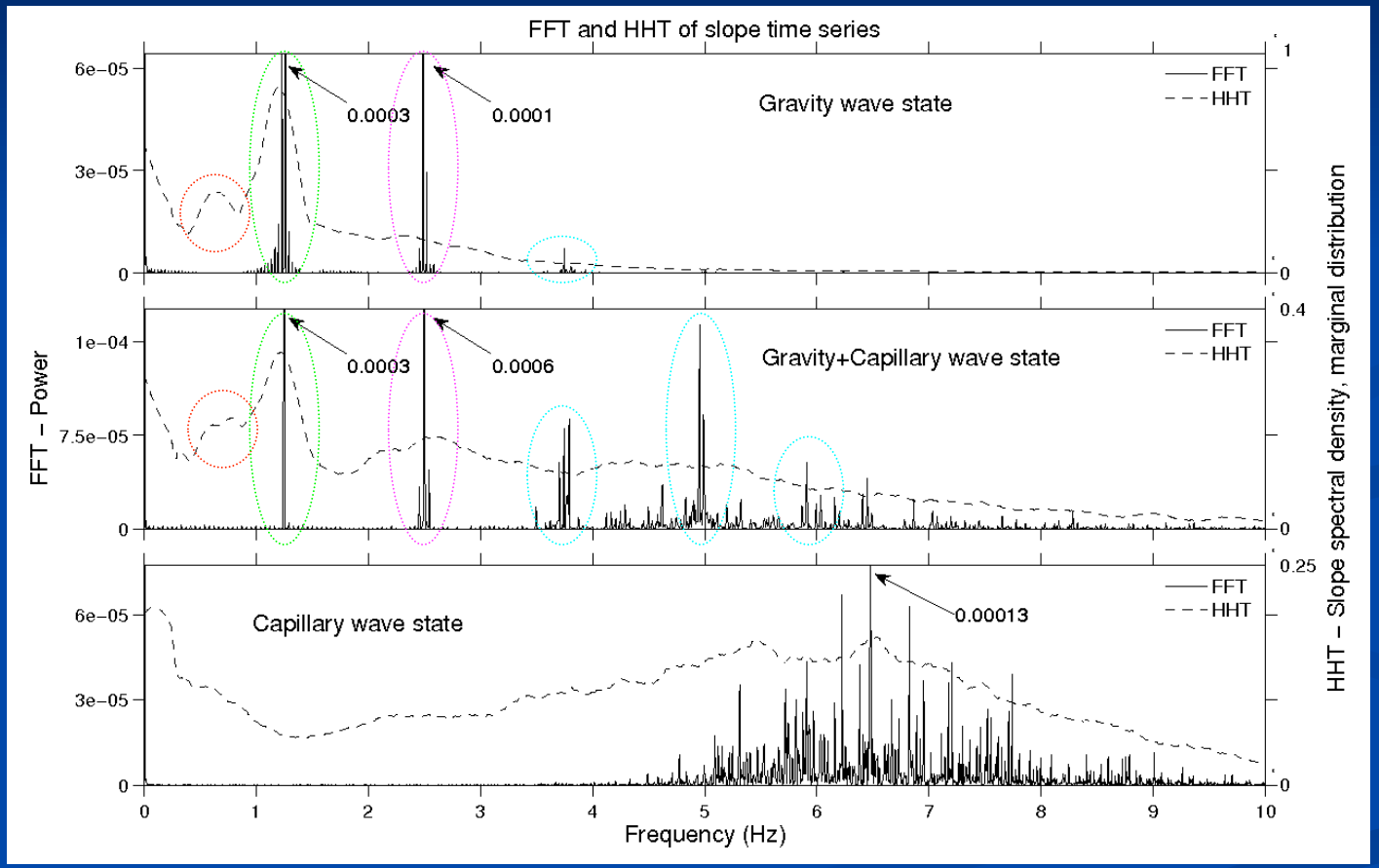
HHT results:

HHT marginal probability vs FFT power spectrum



Sub-harmonic

Paddle (1.25 Hz)

2nd harmonic

Higher-order harmonics

The HHT does not rely on harmonics

Conclusions

- Integrated experimental apparatus successfully detects BRDF signatures over a (controlled) wavy water surface
- Fresnel nature of "atomic" glints outlined
- Statistical analysis shows the fundamental differences between gravity and capillary glints, with glints originating from a mixed state behaving essentially like capillary glints
- Gravity attractor-plot features successfully interpreted in terms of glint time series and surface statistics
- Illustrated the merits of the HHT technique in describing non-linear, non-stationary systems such as water waves

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Midnight at Nordaustlandet,

Svalbard